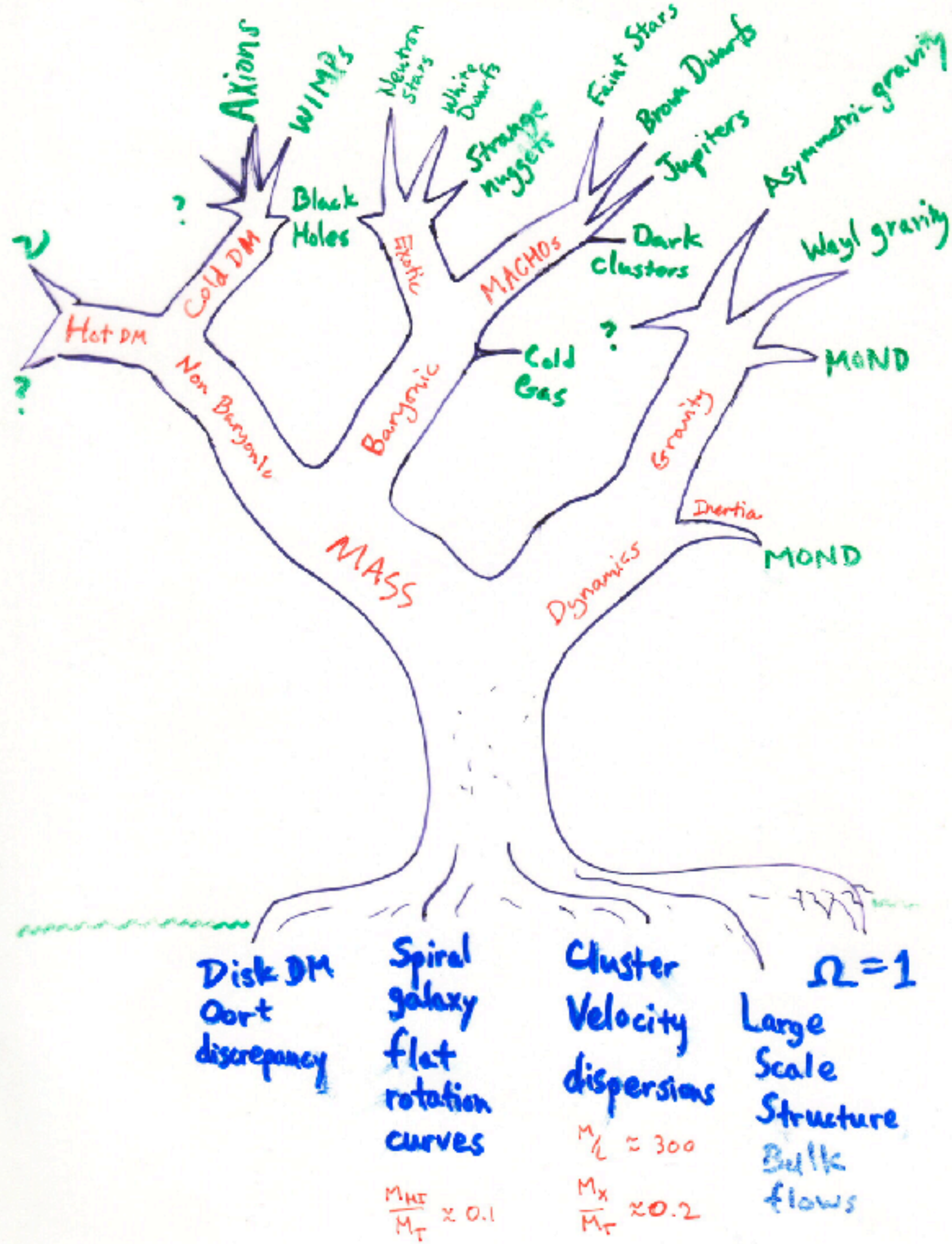
Dark Matter

ASTR 333/433

Today
The Radial Acceleration Relation
Halo models

Homework 2 due March 1
(next class)

Review March 6
Midterm March 8



The Mass Discrepancy-Acceleration Relation

(precursor to the Radial Acceleration Relation)

The distribution of mass is coupled to the distribution of light.

Quantify by defining the Mass Discrepancy:

$$\mathcal{D} = \frac{V^2}{V_b^2} \approx \frac{M_{tot}(< R)}{M_b(< R)}$$

The Mass Discrepancy correlates with acceleration

Baryonic mass models

$$V_b^2(r) = V_{bulge}^2(r) + V_{disk}^2(r) + V_{gas}^2(r)$$

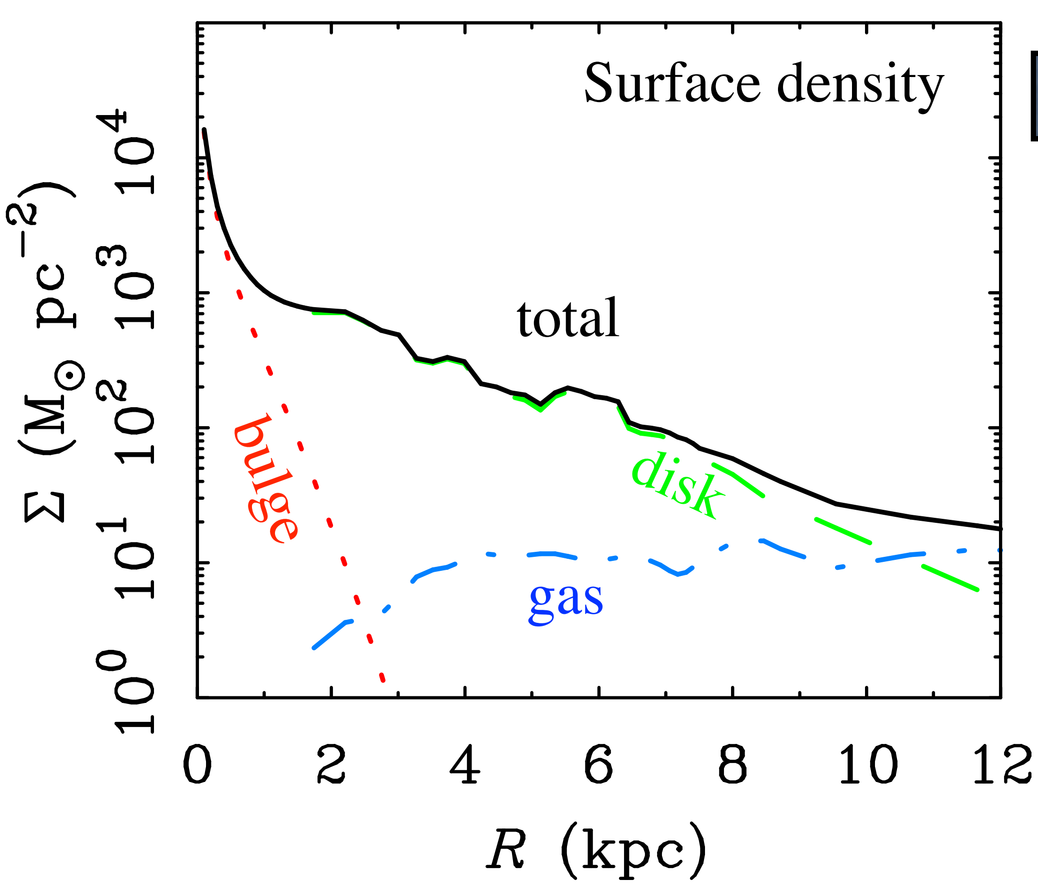
depends on M*/L

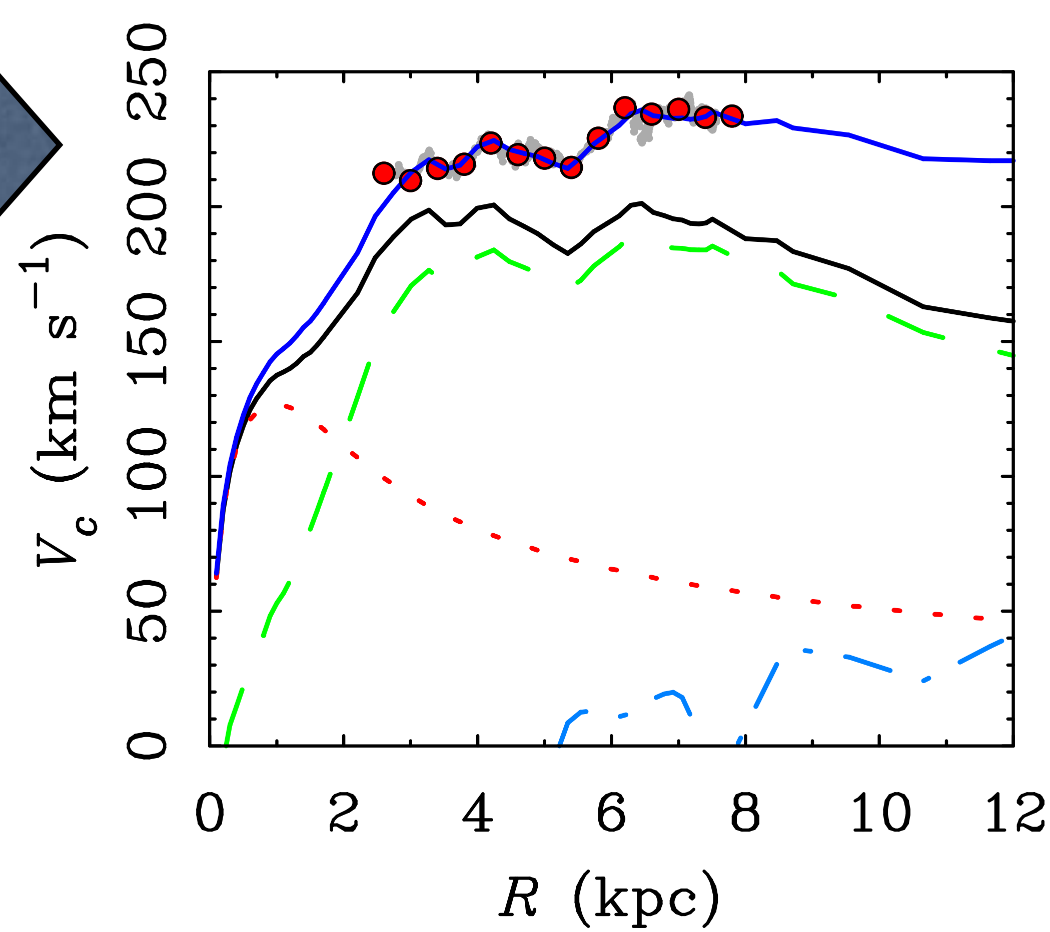
- Bulge
  - often treated as $r^{1/4}$ sphere
  - not always spherical; sometimes more bar-like
- Stellar Disk
  - exponential a crude approximation
  - in practice, solve numerically for the observed surface brightness profile with DISKFIT or ROTMOD (in GIPSY)
- Gas disk
  - usually just HI; CO tracks stars

Example mass model: Milky Way structure

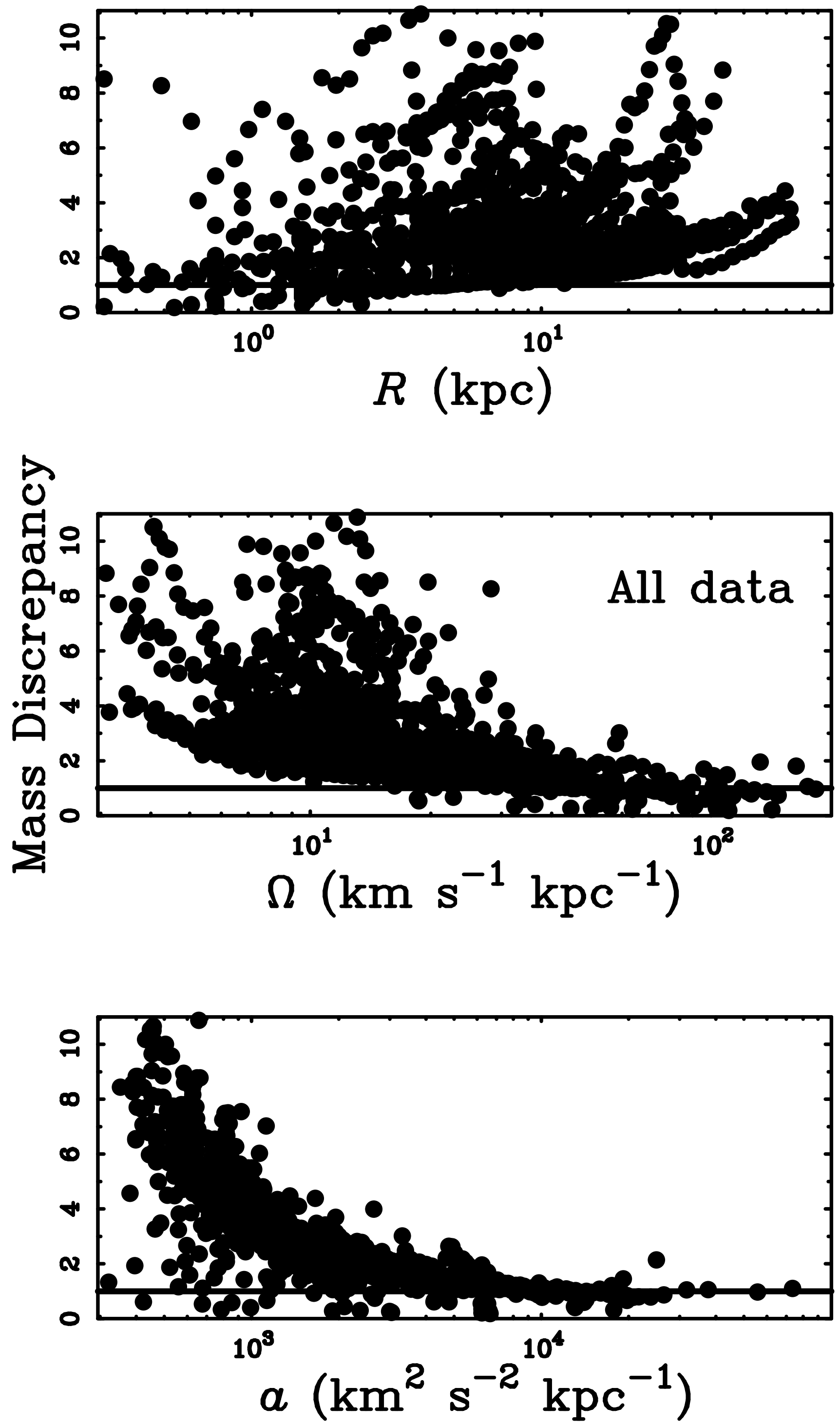
$$g = \frac{V^2}{R} = -\frac{\partial \Phi}{\partial R} = 2\pi G \Sigma(R)$$

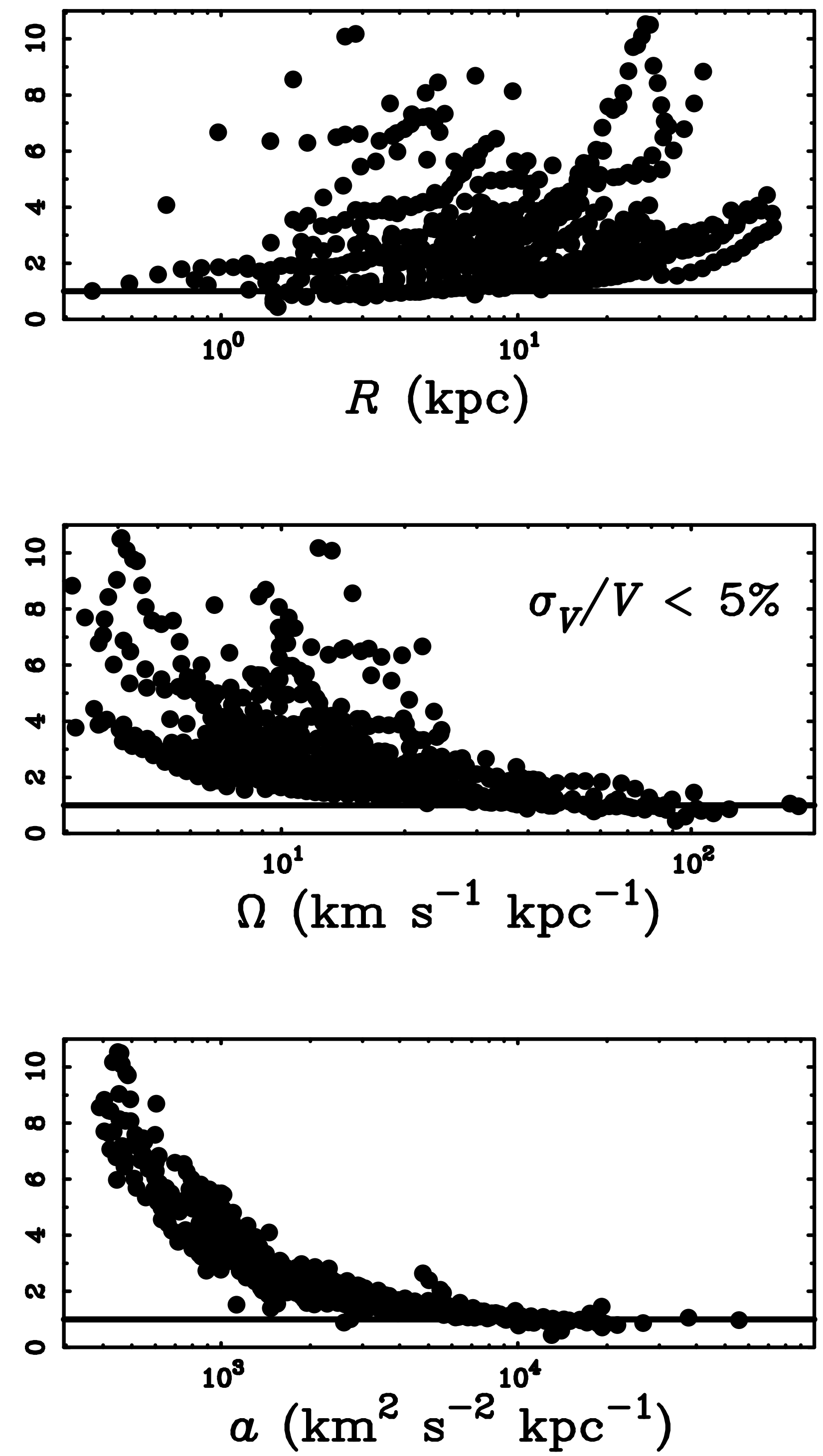
For an observed mass distribution, solve the Poisson equation numerically for the corresponding gravitational potential. Can do this separately for each mass component.





$$\mathcal{D} = \frac{V^2}{V_b^2}$$





radius

orbital frequency

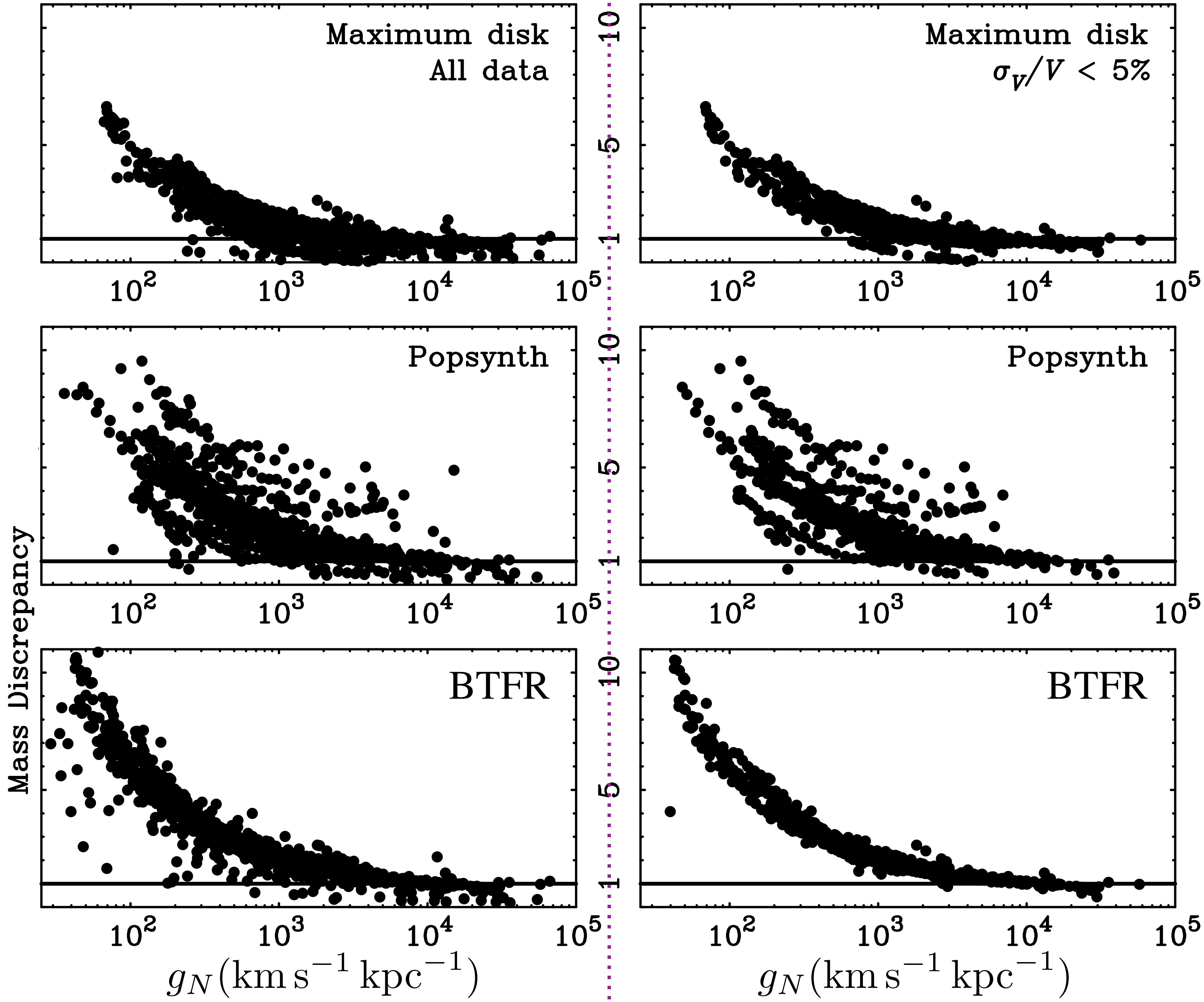
acceleration

74 galaxies
> 1000 points
(all data)

60 galaxies
> 600 points
(errors < 5%)

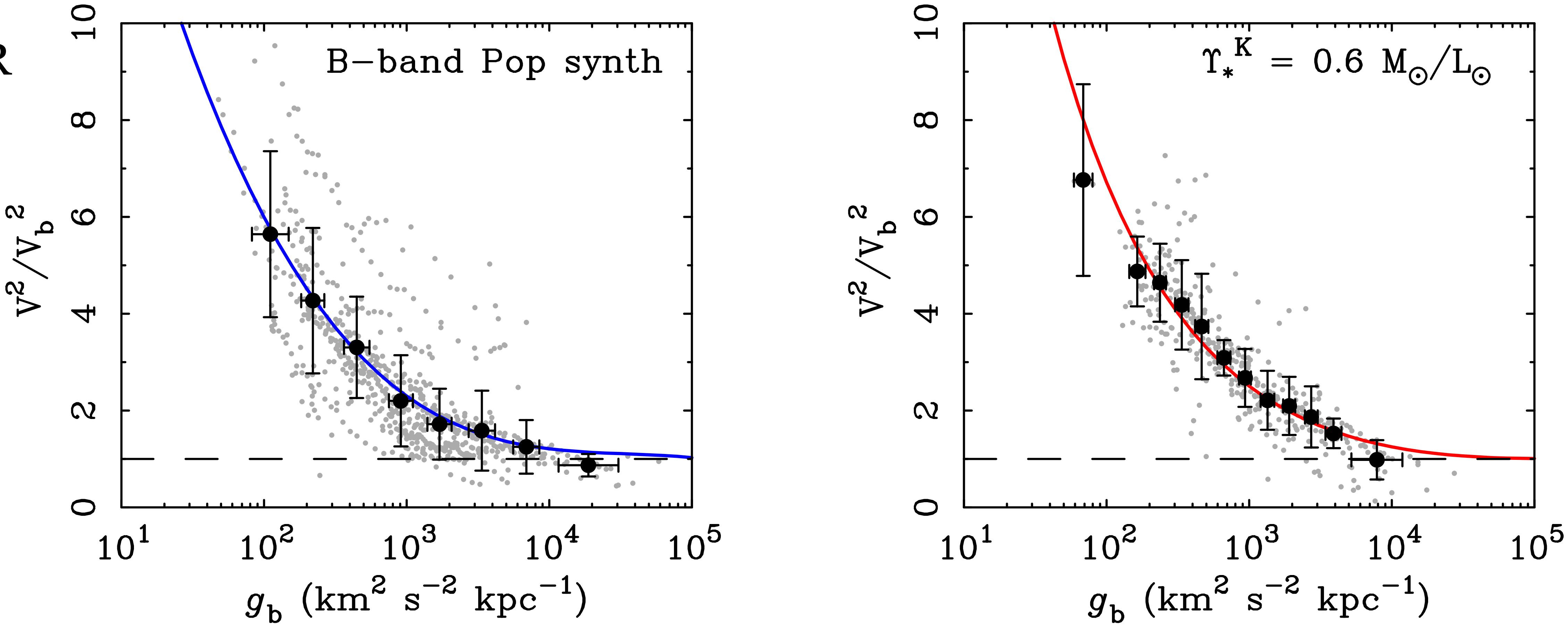
McGaugh (2004)

$$\mathcal{D} = \frac{V^2}{V_b^2}$$



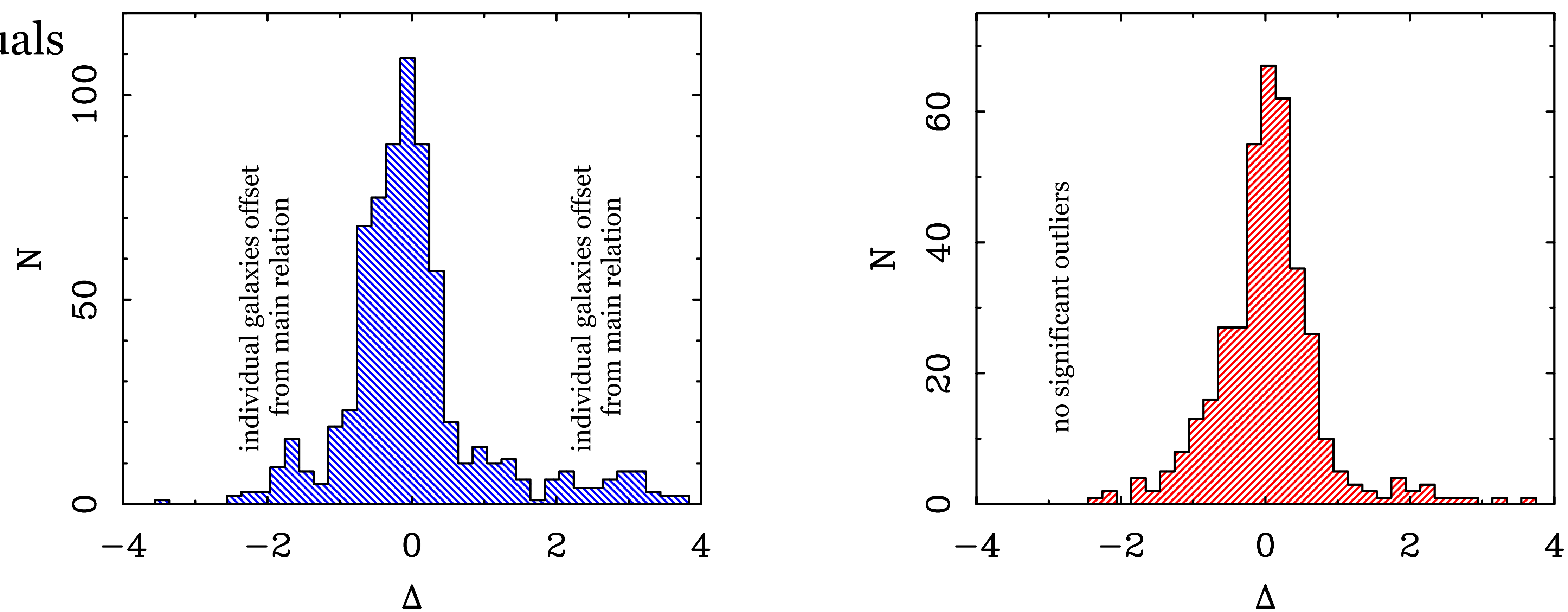
The relation between the mass discrepancy and acceleration persists for any plausible choice of M*/L

MDAR

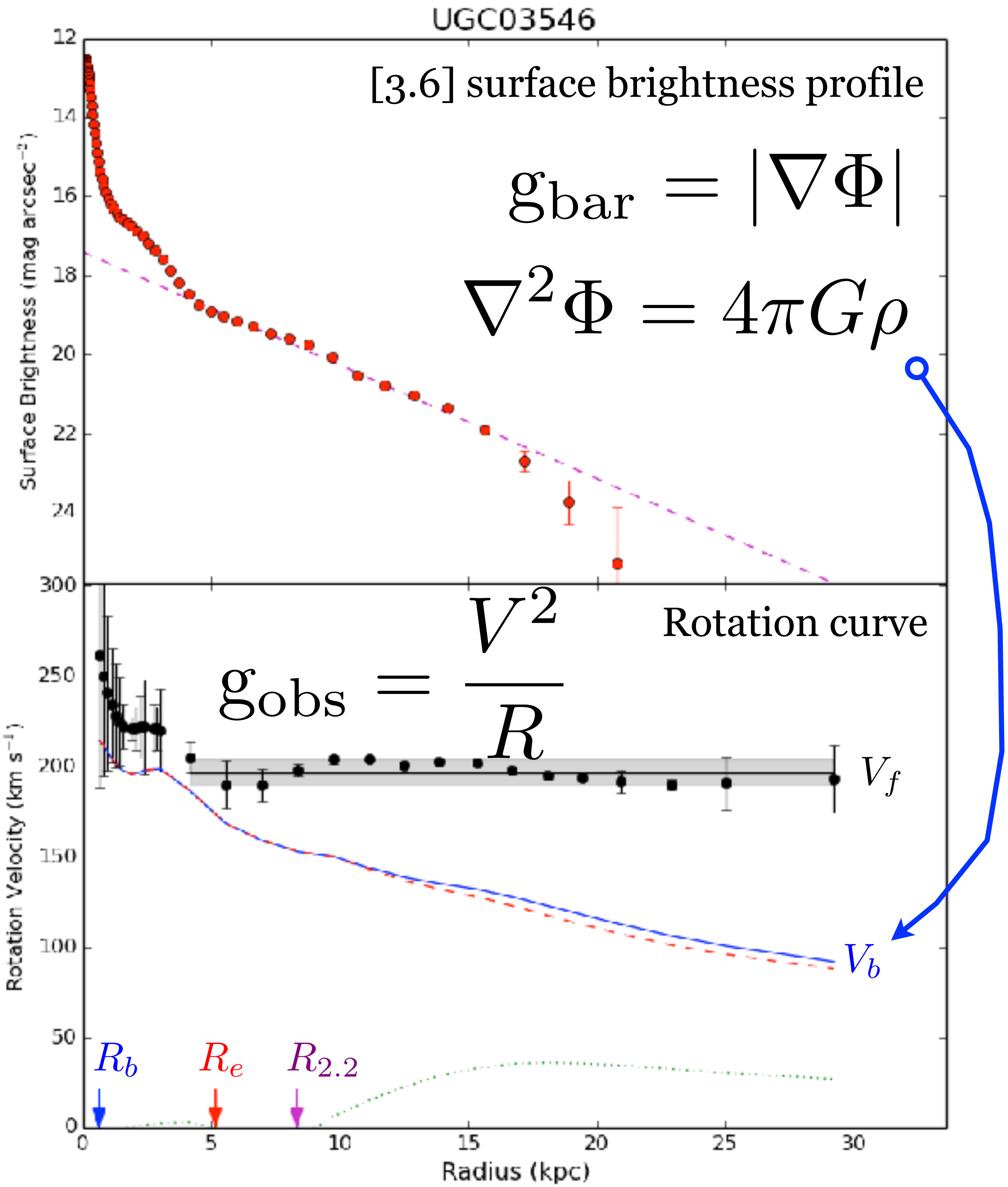


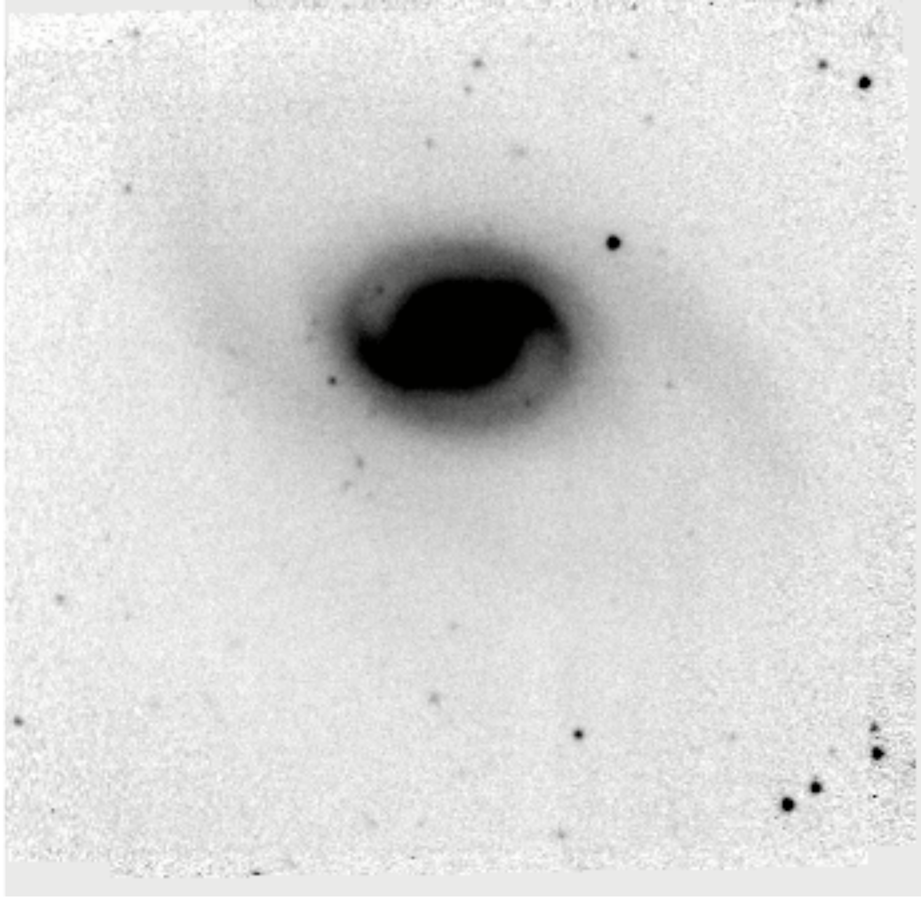
Individual rotation curves perceptible when optical mass models are used, but not with near-IR data for which it suffices to assume a constant M*/L.

Residuals

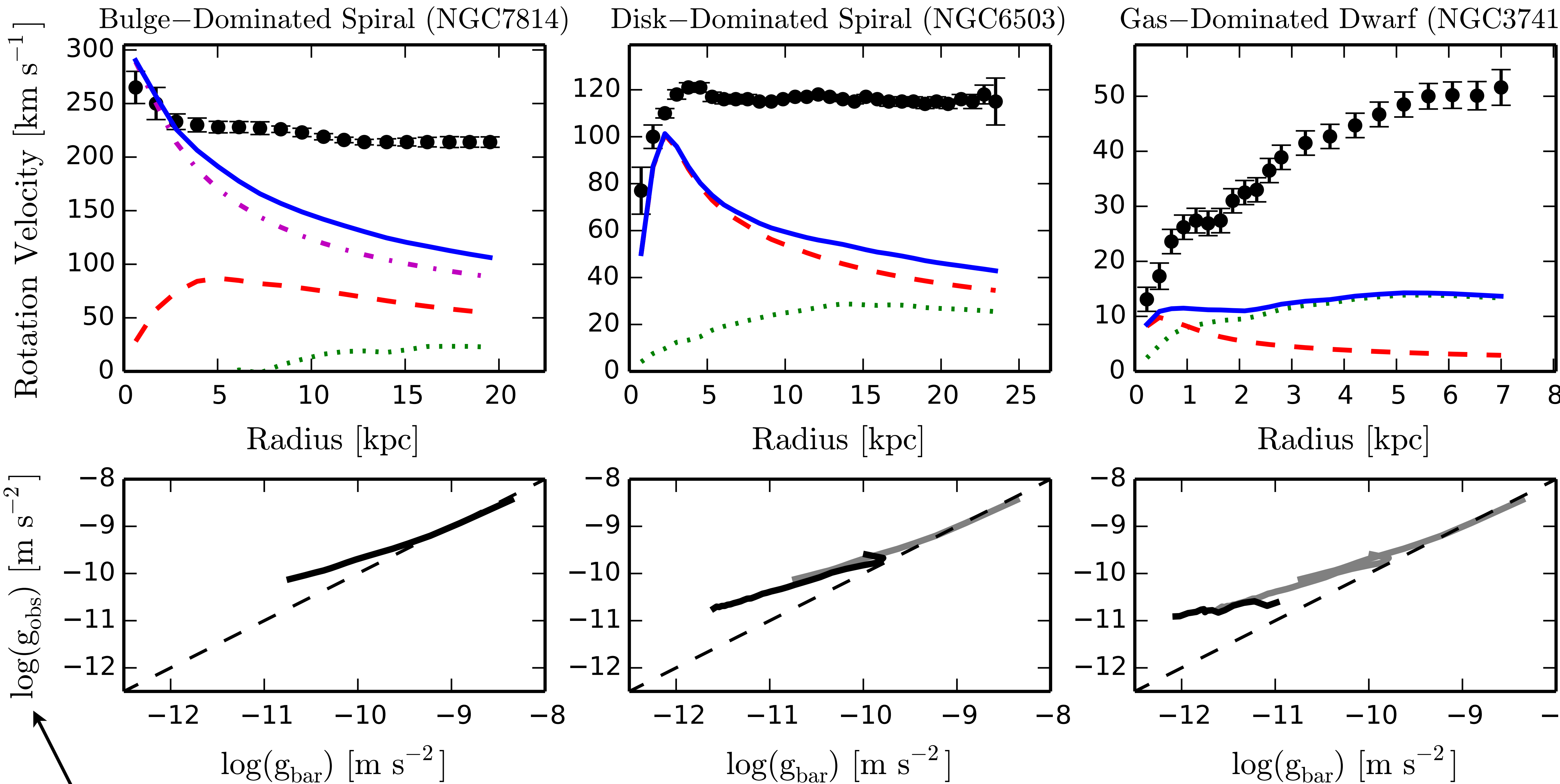


What is happening?





The observed centripetal acceleration is linked to that predicted by the observed distribution of baryons.



$$g_{\rm obs} = \frac{V^2}{R}$$

independent quantities

$$g_{\rm bar} = \left|\frac{\partial \Phi}{\partial R}\right|$$

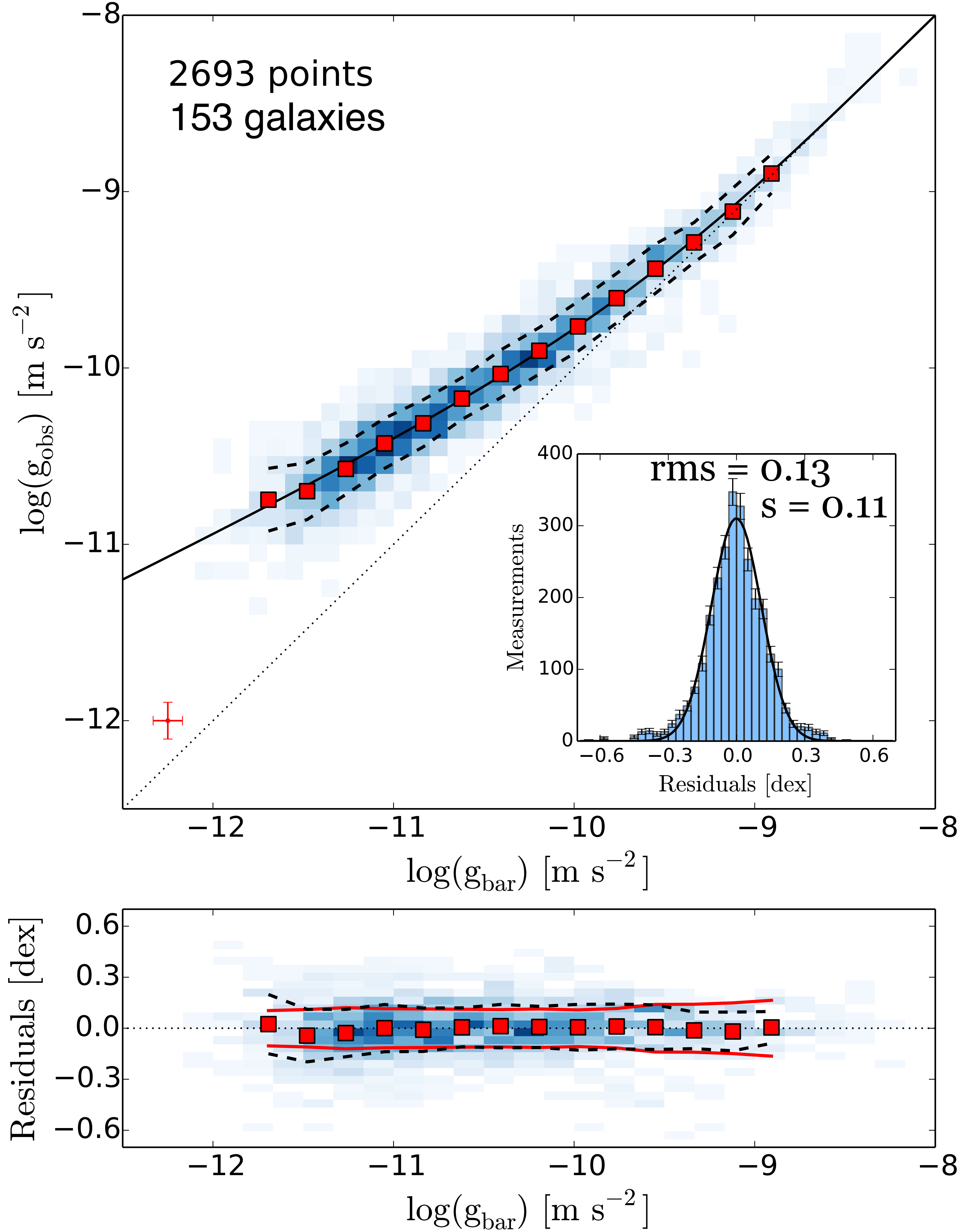
determined from rotation curve

determined from baryon distribution

Radial Acceleration Relation

Constructed from 153 galaxies with 21cm rotation curves and near-IR surface photometry from the *Spitzer* space telescope.

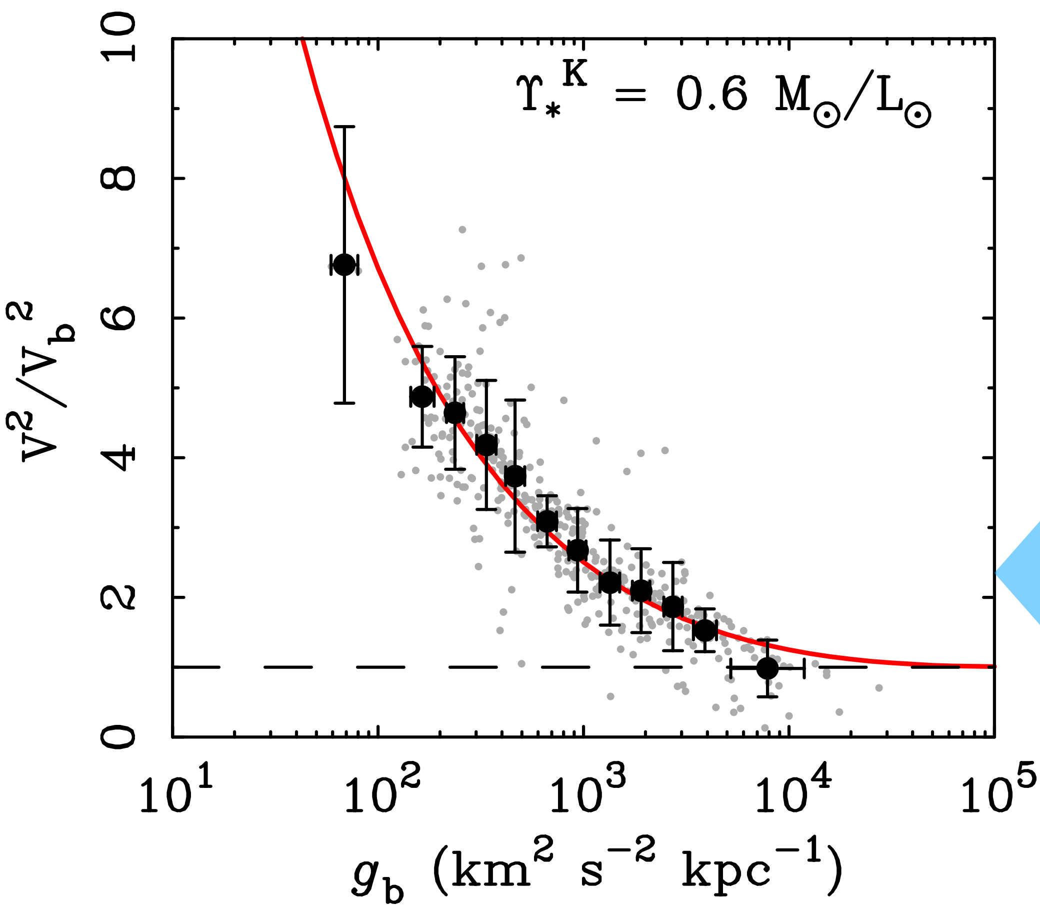
Apparently the mass-to-light ratio in the near-IR is close to constant: individual galaxies do not stand out in this relation.



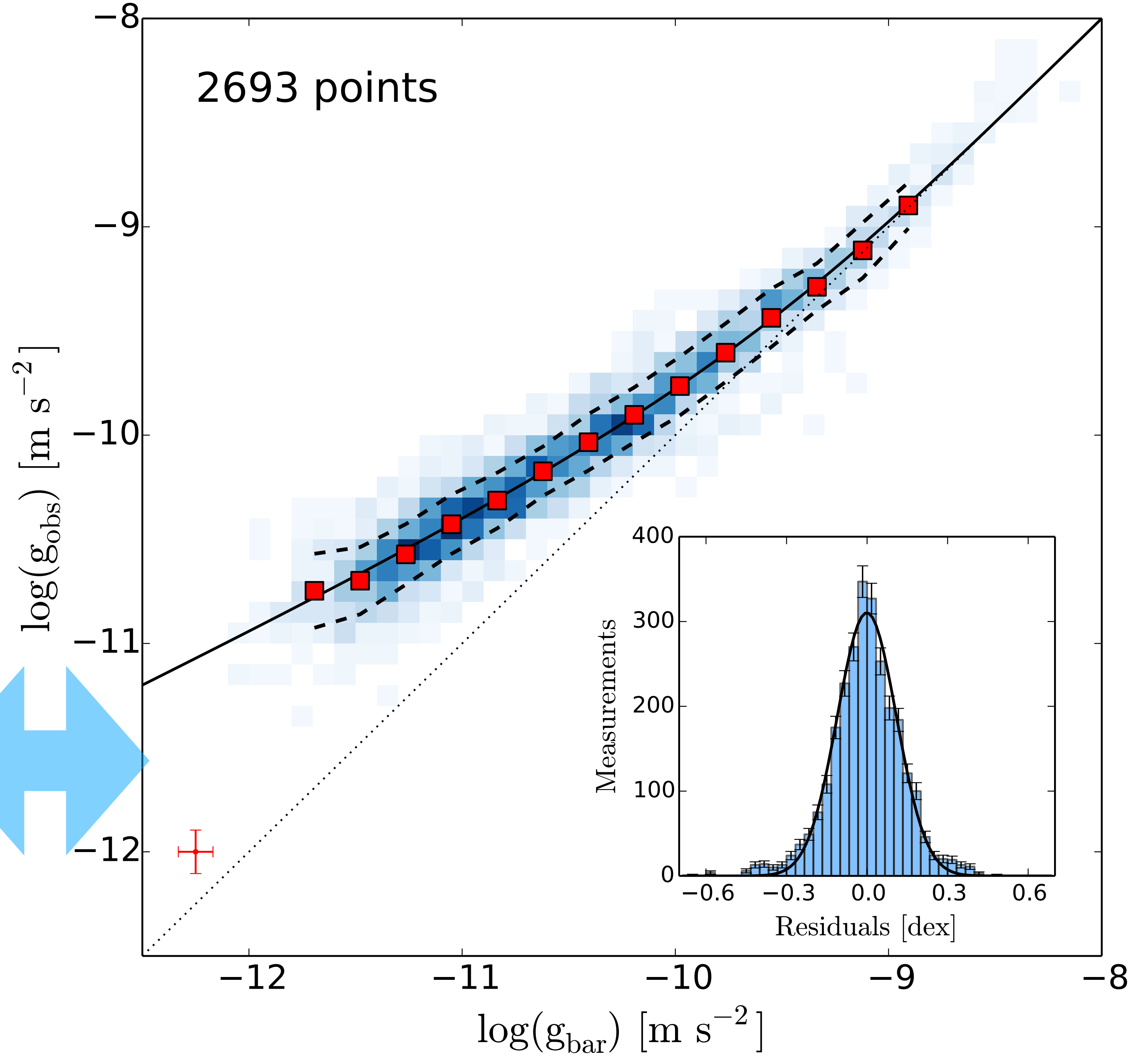
The Radial Acceleration Relation is equivalent to the Mass Discrepancy-acceleration relation, just with independent x & y axes.

$$\mathcal{D} = \frac{g_{obs}}{g_{bar}} = \frac{V^2}{V_b^2}$$

MDAR



RAR



Radial Acceleration Relation

well fit by

$$g_{obs} = \frac{g_{bar}}{1 - e^{-\sqrt{g_{bar}/g_{\dagger}}}}$$

$$g_{\dagger} = 1.20 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

± 0.02 (random) $\pm$ 0.24 (systematic)

observed rms scatter - - - - - - - - - -

scatter expected from observational errors ———

The data are consistent with zero intrinsic scatter

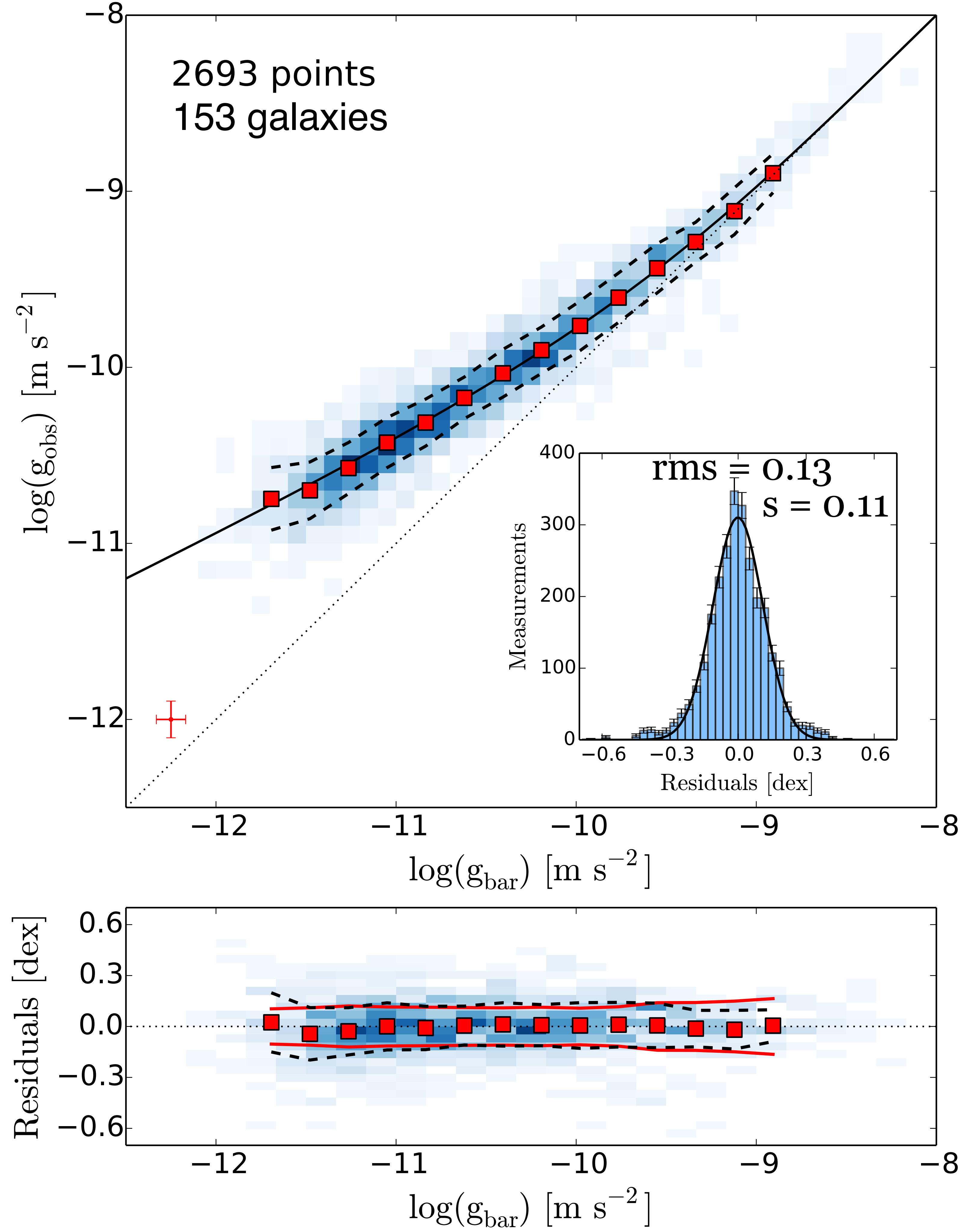
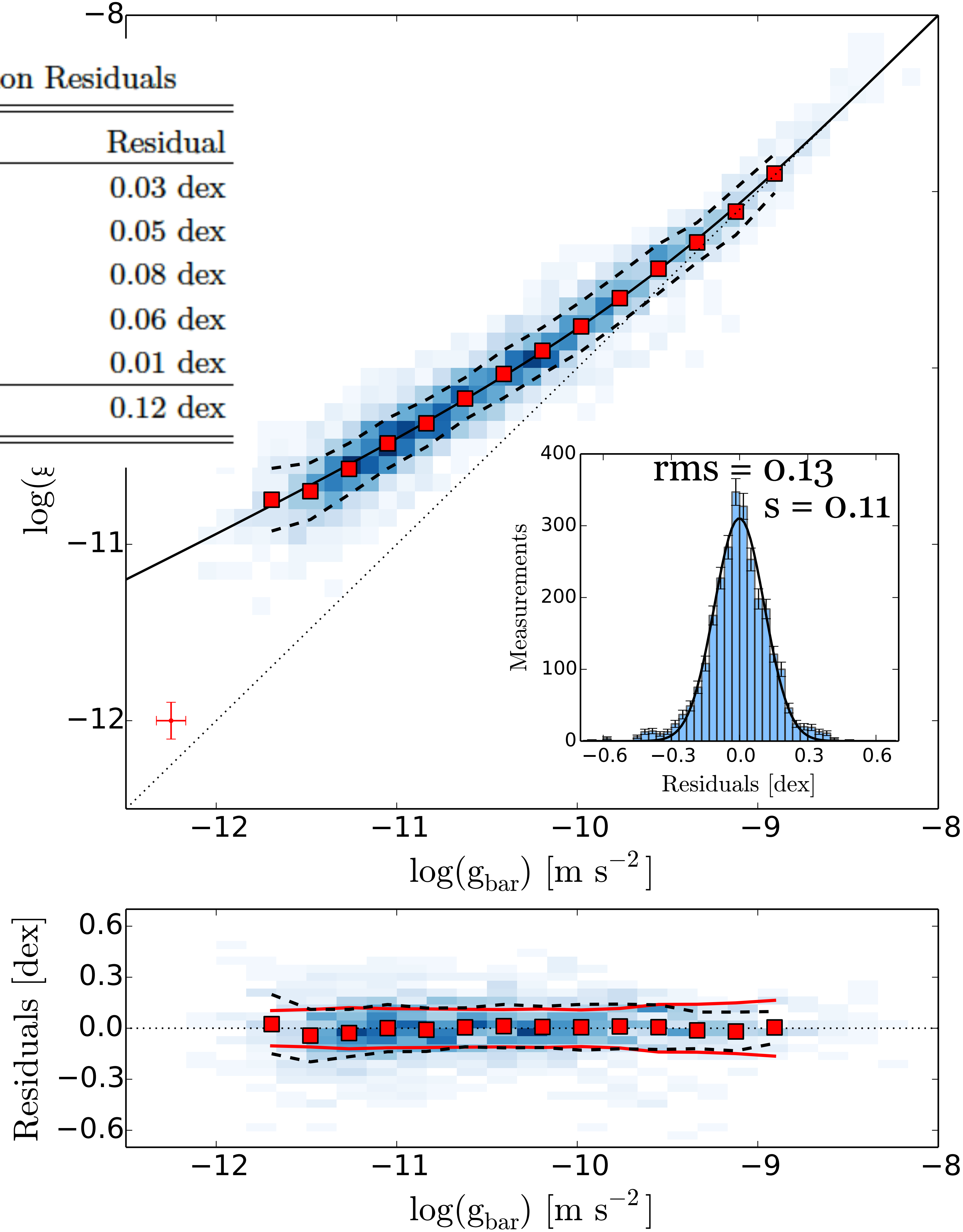


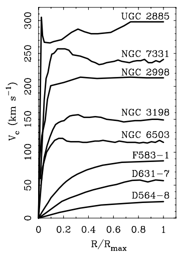
TABLE I. Scatter Budget for Acceleration Residuals

Source	Residual
Rotation velocity errors	0.03 dex
Disk inclination errors	0.05 dex
Galaxy distance errors	0.08 dex
Variation in mass-to-light ratios	0.06 dex
HI flux calibration errors	0.01 dex
Total	0.12 dex

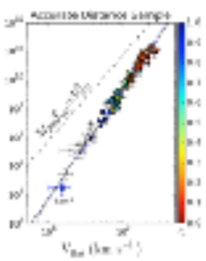


Measurement errors tend to become more important at lower accelerations while galaxy-to-galaxy variations in the mass-to-light ratio tend to become less important.

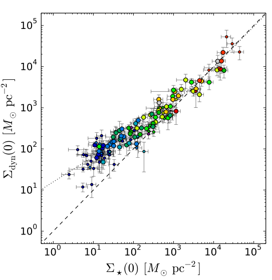
Laws of Galactic Rotation



- Rotation curves tend towards asymptotic flatness $V_f \rightarrow \mathrm{constant}$

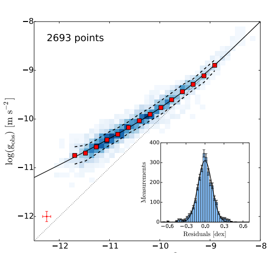


- Baryonic mass scales as the fourth power of rotation velocity (Baryonic Tully-Fisher Relation) $M_b \propto V_f^4$



- Central mass surface density scales with central surface brightness

1:1 at high density; $\Sigma_{dyn} \sim \Sigma_*^{1/2}$ at low density



- Centripetal acceleration specified by the baryon distribution

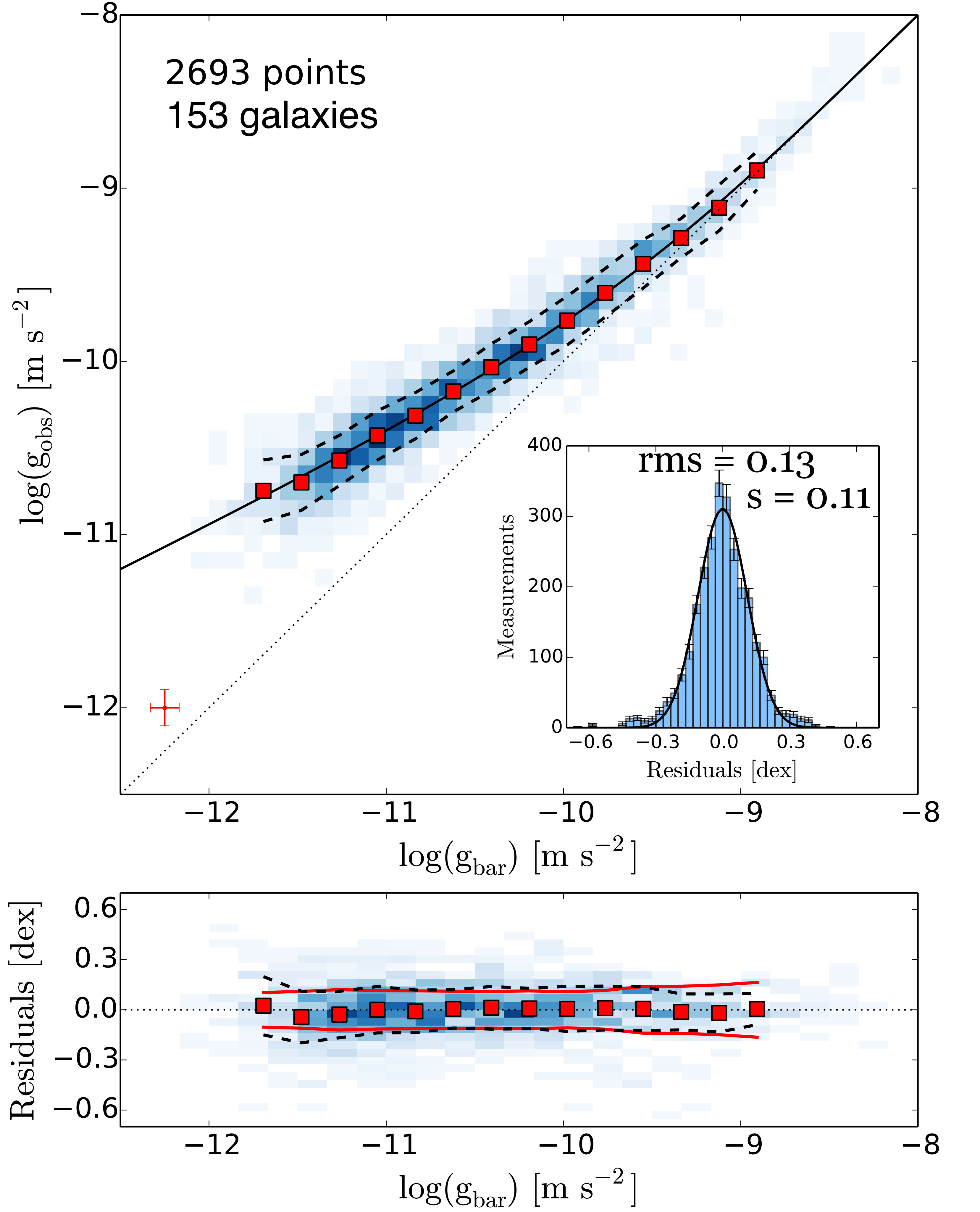
$$\mathrm{g_{bar}} = -\frac{\partial \Phi_b}{\partial R} \quad \text{predictive of} \quad \mathrm{g_{obs}} = \frac{V^2}{R}$$

Surface density and acceleration are key parameters, related by $\mathrm{g} \propto G\Sigma$

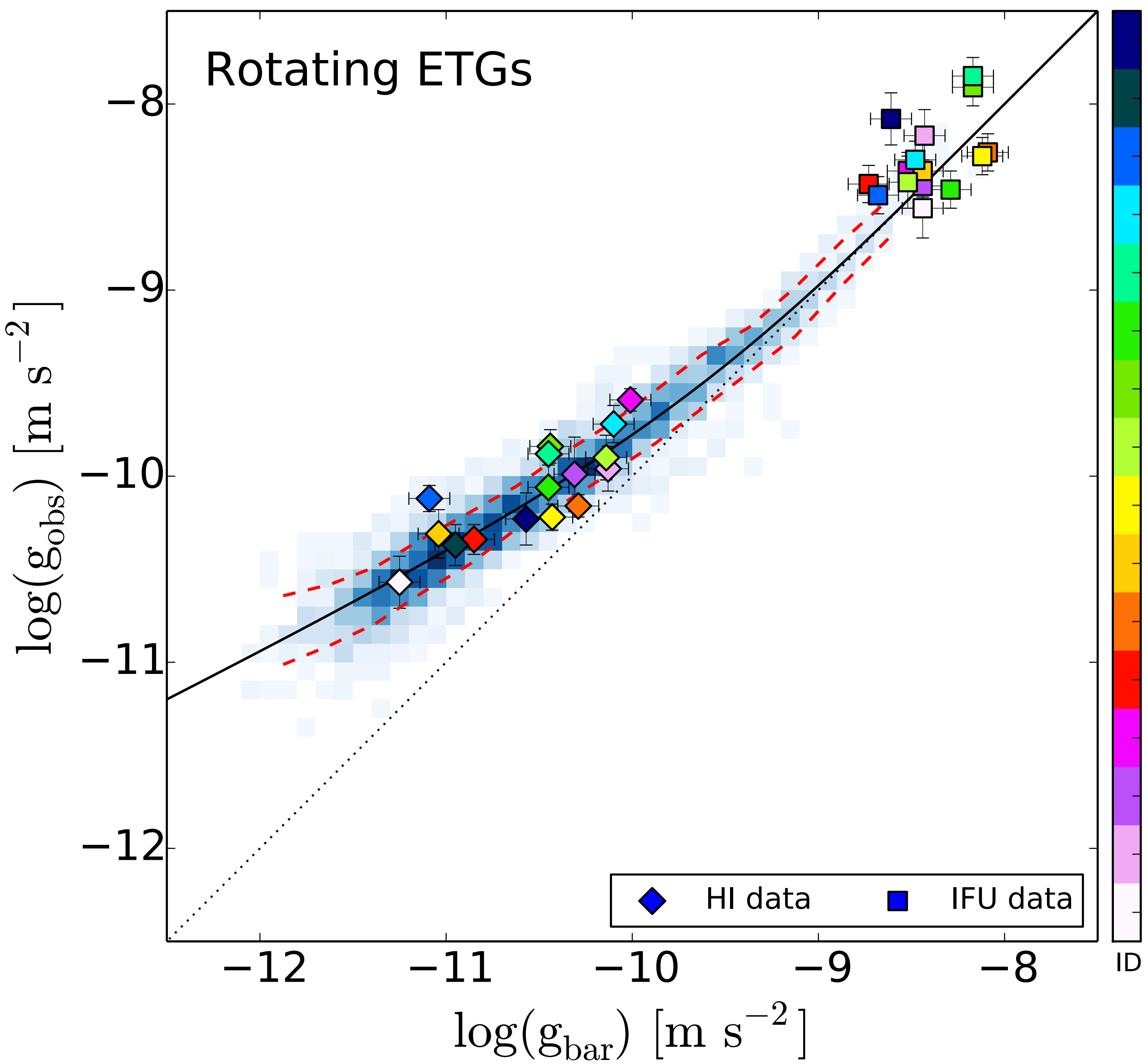
The first three follow from the Radial Acceleration Relation

Radial Acceleration Relation

So far, just talking about rotating galaxies. What about pressure supported Ellipticals?

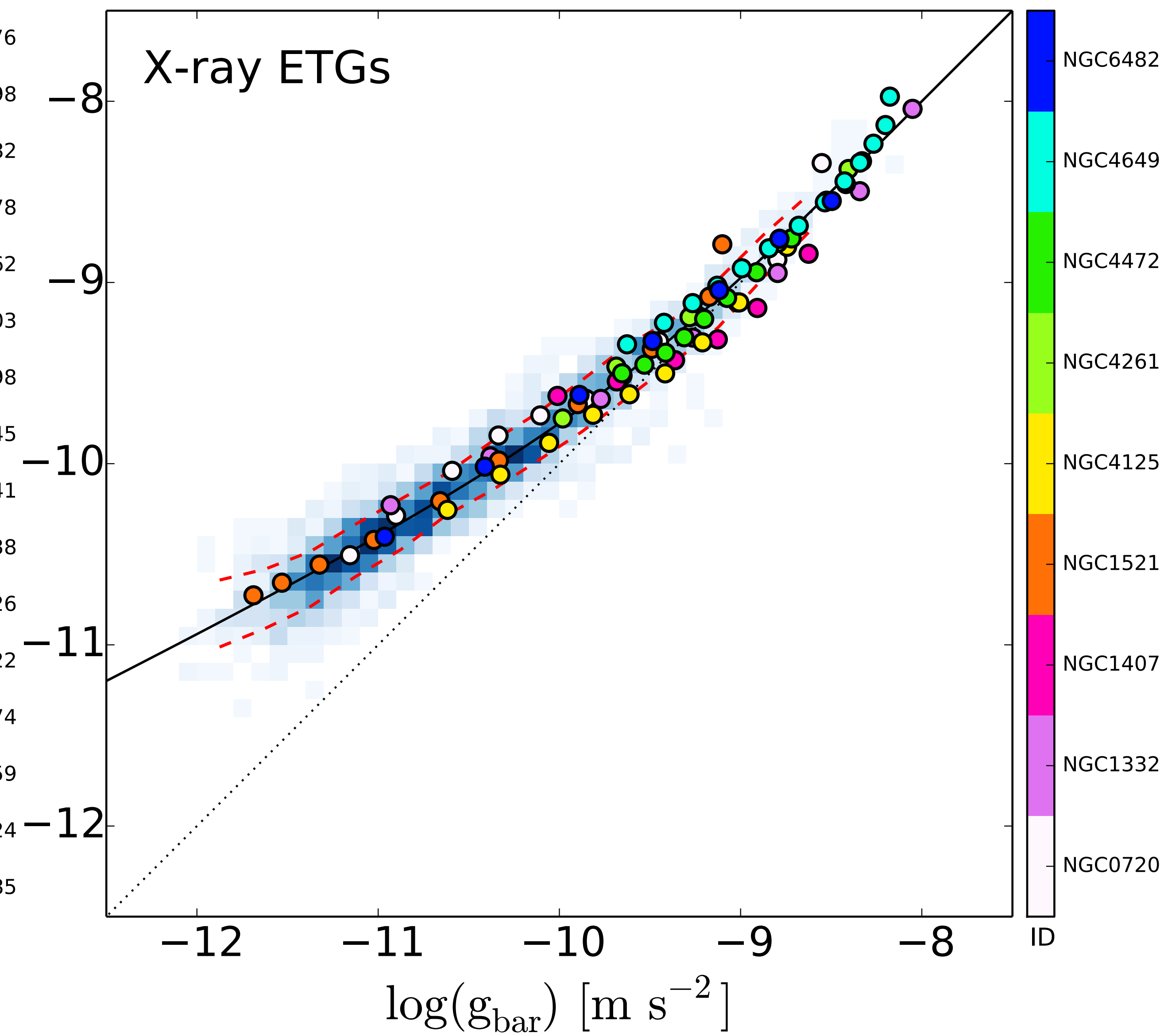


ATLAS^{3D} data (fast rotators)

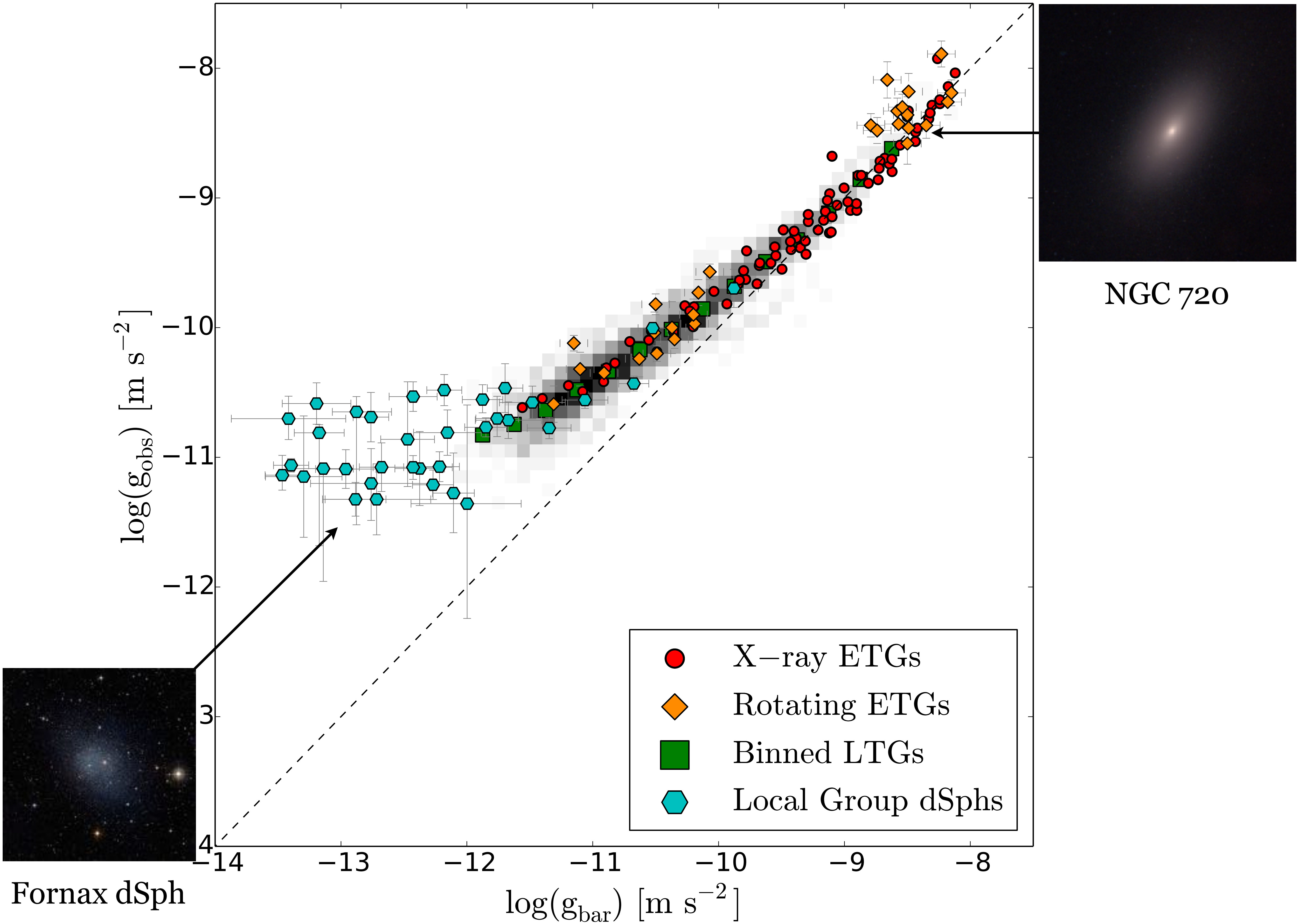


Inner, high acceleration data from optical IFU
Outer, low acceleration points from HI 21 cm

X-ray Ellipticals (slow rotators)



Mass profiles from hydrostatic equilibrium of X-ray gas.



−8
−9
−10
−11
−12
$\log(g_{obs})$ [m s^{-2}]
−14
−13
−12
−11
−10
−9
−8
$\log(g_{bar})$ [m s^{-2}]
X−ray ETGs
Rotating ETGs
Binned LTGs
Local Group dSphs
NGC 720
Fornax dSph

Dark Matter

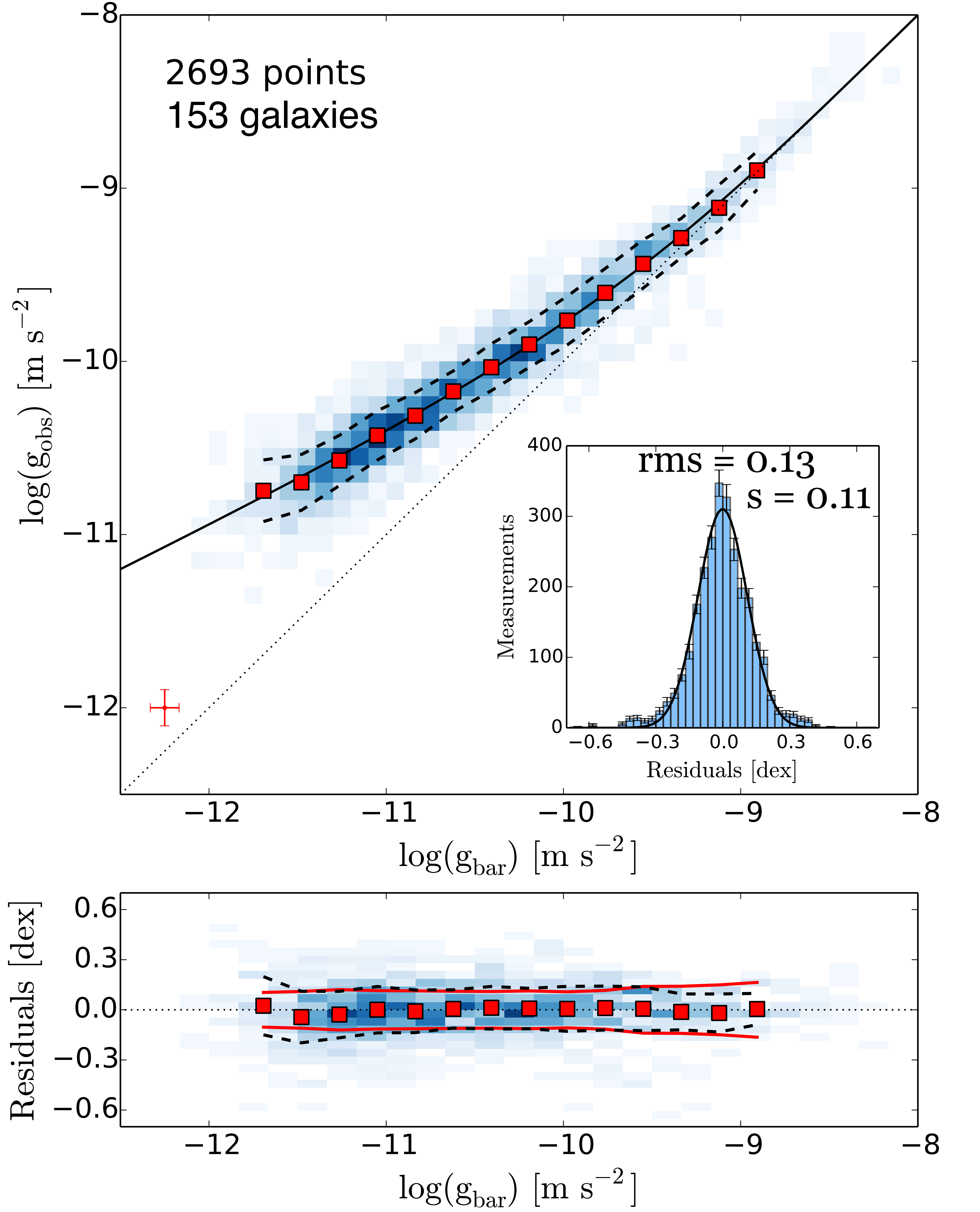
Radial Acceleration Relation

One consequence:
the dark matter distribution is strongly coupled to the baryons

$$g_{obs} = \frac{g_{bar}}{1 - e^{-\sqrt{g_{bar}/g_{\dagger}}}}$$

$$g_{DM} = g_{obs} - g_{bar}$$

You can work out the dark matter distribution just by looking at the baryons



Dark Matter - one consequence

The Radial Acceleration Relation can be used to infer the dark matter distribution just by looking at a galaxy.

total $\quad g_{\mathrm{obs}} = \mathcal{F}(g_{\mathrm{bar}})$

$$\mathcal{F} = \frac{g_{\mathrm{bar}}}{1 - e^{-\sqrt{g_{\mathrm{bar}}/g_{\dagger}}}}$$

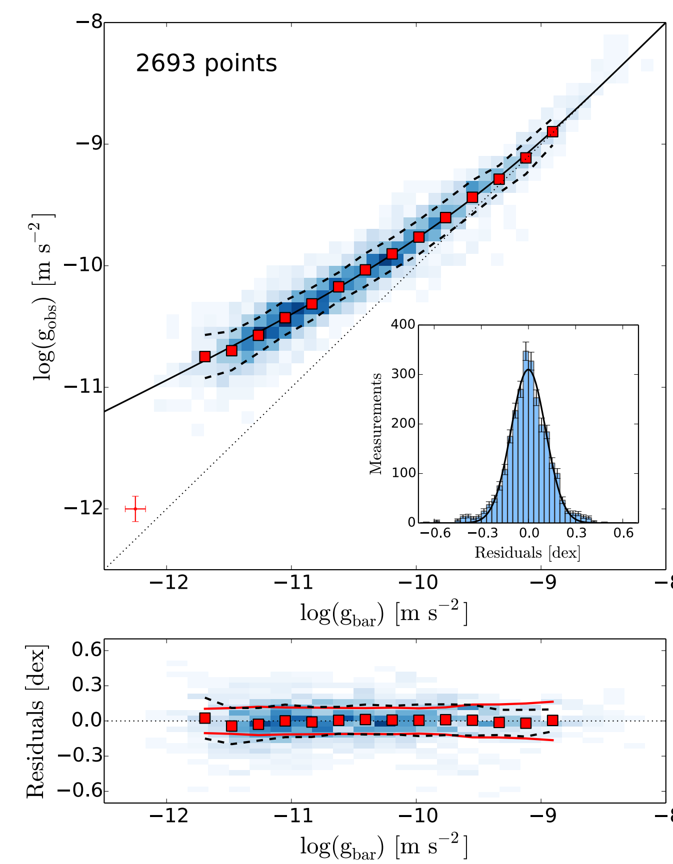
dark matter $\quad g_{\mathrm{DM}} = g_{\mathrm{obs}} - g_{\mathrm{bar}}$

$$g_{\dagger} = 1.20 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

± 0.02 (random) $\pm\ 0.24$ (systematic)

$$g_{\mathrm{DM}} = \mathcal{F}(g_{\mathrm{bar}}) - g_{\mathrm{bar}}$$

The dark matter distribution is specified by the baryon distribution



That's weird

A more natural interpretation would be that the baryons are the source of the gravitational potential. That would imply a modification of gravity (i.e., MOND) rather than dark matter.